Fermi National Accelerator Laboratory

Summary of the Accelerator Working Group

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Disclaimer

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Abstract. We present a summary of the main topics discussed in the Accelerator Working Group during the "Workshop on the Physics at the First Muon Collider". The discussions centered on critical design issues for a high-intensity, medium-energy proton synchrotron that would replace the present Fermilab 8 GeV Booster early in the next century. Such a machine is intended both to serve the hadron program with an order of magnitude increase in average proton current and to be compatible as a source for a future muon collider. Particular issues discussed at length include rf system design, control of longitudinal space-charge effects, bunching of proton beams and beam instabilities.

INTRODUCTION

The Accelerator Working Group at the workshop had two charges: to provide accelerator expertise to the other working groups and to advance the design of the so-called proton driver for the muon collider. The purpose of the proton driver is to provide a few intense short bunches at the pion production target. A promising approach to meet the demanding specifications for the proton driver has evolved in the last eighteen months or so. These design concepts were documented and a provisional set of accelerator parameters were defined as the result of a 1997 Proton Source Summer Study at Fermilab. Fermilab Technical Memo TM-2021, entitled "A Development Plan for the Fermilab Proton Source," edited by S.D. Holmes, describes those concepts and presents the resulting parameters [1]. It is important to note that the proposed facility would not only meet the needs of the muon collider but also substantially enhance future hadron programs at Fermilab.

To insure a consistent set of parameters across all the working groups at the muon workshop, the organizers decided to standardize on the design and the parameters described in TM-2021. That document can be consulted for a detailed description of the design concepts and parameters; for convenience a brief overview is provided here.

The proton driver consists of two proton synchrotrons in series. They are both rapid-cycling (15 Hz) machines. The harmonic number of the first ring, h=2, is chosen to allow the two intense bunches of protons required for the muon collider to be accelerated. For convenience in matching to the requirements of the hadron program, the rf bucket spacing in both machines is chosen to be a multiple of that in the existing proton accelerators at Fermilab. Also the second ring is assumed to have the same circumference as the existing Fermilab Booster. The first ring is fed by a 1 GeV linac and accelerates to 4.5 Gev; the second ring accelerates to 16 GeV. For the muon collider, the two bunches accelerated in the first ring would be injected into the second ring and accelerated to 16 GeV. However, the first ring can also be bypassed and the 1-GeV beam injected directly into the second ring in order to fill all 21 buckets of the second ring. That mode would be useful for filling the Main Injector rapidly as well as perhaps for providing slow-spill beam at 16 GeV from the new Booster complex. For the latter purpose a stretcher ring would be provided in the same tunnel as the second ring.

Overcoming space charge effects, both longitudinal and transverse, is a dominant consideration in the design of these rings. In order to alleviate transverse effects, high injection energies and large transverse emittances are used. Also the bunches are kept relatively long in each machine until the end of the acceleration cycle, at which time a bunch-narrowing rotation in longitudinal phase space is induced by the appropriate rf gymnastics. The rf frequency in the second ring is four times higher than that of the first ring to match the bucket parameters to the shape of the rotated bunch. (Since the workshop a new set of parameters with a harmonic number of four in the first ring and no frequency jump between rings has been found to be promising.)

RF SYSTEM DESIGN FOR A HIGH-INTENSITY SYNCHROTRON

As noted in the Introduction, the second ring of the Booster replacement is chosen to have the same circumference as the present 8 GeV machine (475 m) as an operational convenience for anti-proton collection and Main Injector filling. With normal-conducting resonant magnets, the maximum field with present technology is about 1.3 T. Assuming roughly the same fraction of the circumference as in the present Booster is needed for rf injection, extraction and focusing, the maximum energy that could be accomodated in the ring is about 16 GeV. Assuming 33 msec available at the desired 15 Hz repetition rate for acceleration over a 12 GeV range, the rf voltage per turn is about 500 kV. The proton bunches must be shortened to 1 to 2 nsec (rms) for targeting. The longitudinal emittance must be kept below 4 eV-sec so the final momentum spread at 16 GeV does not exceed five percent, at which point lattice design becomes difficult.

The need for 5×10^{13} protons per bunch in only two bunches suggests that space-charge potential well distortion of the rf bucket and transient beam loading

of the accelerator cavities could be so large as to prevent successful bunching if not corrected. The potential well distortion can be countered generally by raising the rf voltage, increasing the beam momentum and adding inductance to cancel the capacitive space-charge induced voltage. Transient beam loading results in wakefields being excited in the accelerator cavities which can affect both the latter part of the generating bunch or successive bunches in the ring. Methods to reduce these wakefield effects are to reduce the R/Q of the cavities (since the wake voltage is proportional to this), increase the bunch spacing by lowering the ring harmonic number and using feedback and/or feedforward to oppose the cavity currents induced by the bunch.

During the workshop, a particular realization of feedback/feedforward was explored to compensate transient beam loading in the proton driver for a muon collider. The concept was first used at the CERN ISR in the 1970's resulting in about ninety percent compensation of the induced wakefield voltage [2]. The method consists of a pick-up, a one-turn delay cable (or half-turn cable with signal sent across the ring diameter), a wide-band amplifier chain and a final amplifier, directly connected to the accelerating gap. This system injects into the cavity a current approximately equal and opposite to the beam current. This amplifier is separate from the amplifier used to provide the nominal accelerating voltage at the fundamental frequency.

Because of the longer bunches in the 4.5 GeV ring, transient beam loading was considered to be not as severe there compared to the second ring. Most discussions during the workshop centered on this first ring due to the limited discussion time. A special break-out group led by M. Popovic, consisting of J. Griffin, Q. Kerns, I. Kourbanis, A. Moretti and D. Wildman, worked out a strawman rf design that could be studied further after the workshop. Each of the two bunches contains 8 μC with a full width of about 80 nsec, corresponding to a peak current of about 100 A. The radio frequency swing in this first ring goes from 2.9 MHz to 3.27 MHz. The cavity is designed to be broad-band with an R/Q of 20, and cavity tuning may not be necessary in this ring. A one-meter cavity is driven by two 600 kW tetrodes, and each of its two gaps produce 20 kV. The tetrodes are mounted directly on the cavity, and each is designed to supply up to 50 A to counteract the beam induced current. The power loss in the cavity ferrite is about 100 kW at 15 Hz requiring active cooling.

CONTROL OF LONGITUDINAL SPACE-CHARGE EFFECTS

The observation that, in principle, the voltage induced back on a bunch via its interaction with an inductor can cancel the capacitive space-charge induced voltage in a synchrotron was made by Sessler and Vaccaro [3]. The cancellation is effective only if the compensator continues to act inductively at wavelengths corresponding to the bunch length. For bunches that are tens of nanoseconds long, this means

the inductor's bandwidth must be of order 10 to 100 MHz.

In the working group, a review of a recent experiment to test passive inductive compensation was presented by J. Griffin. The experiment is described in a recent Fermilab publication [4]. During the summer of 1997, a joint Fermilab-Los Alamos collaboration performed an experiment at the LANL Proton Storage Ring to demonstrate inductive compensation of longitudinal space-charge effects in that machine. Total intensities of up to 3×10^{13} protons were used in the experiments. A set of ferrite cores was assembled at Fermilab into a 1.5 meter long inductor assembly. The inductor permeability is about 50 and the Q is about 100, and each of these properties remains roughly constant up to 40 MHz. With the ferrite installed, the rf voltage required to maintain a stable PSR beam was reduced by thirty percent compared to previous experience, indicating that the ferrite did indeed cancel part of the space-charge induced voltage.

BUNCHING OF PROTON BEAMS BEFORE TARGETING

Muon collider designs require that the pions from which muons are produced be generated in a short bunch to keep the initial longitudinal emittance low and improve the separation between polarization states. Muon collection simulations suggest that the rms bunch length of the protons on target should be 1 to 2 nsec. Several methods of producing short bunches have been suggested including (1) debunching by lowering the rf voltage followed by a one-quarter synchrotron revolution in the mismatched bucket when the voltage is increased, (2) rebunching at a higher radio frequency, (3) operating near transition where the bunch length is naturally short and (4) use of specialized linacs, beamlines and bunching rings.

Because solution (1) is a well-understood, standard method in accelerators today, it has been studied extensively to see if it can produce nanosecond-long bunches for a muon collider. Reports by I. Kourbanis and Z. Qian on simulations of this method were made in the working group. The multiparticle, longitudinal dynamics code ESME was used to study proton bunch evolution through the complete process of multi-turn injection at 1 GeV, acceleration in the first ring to 4.5 GeV, transfer to the second ring, acceleration to 16 GeV and finally rf bunch rotation prior to extraction. Both synchrotrons operate below transition (transition gammas of 7 and 25, respectively) to reduce the possibility of longitudinal microwave instability. Two bunches each of intensity 5×10^{13} protons were used in the simulation. At 16 GeV a final bunch length of 5.2 nsec (95 % full width) was achieved. The longitudinal emittance in the second ring grew from 1.8 eV-sec to 2.5 eV-sec with three percent particle loss.

The use of some second harmonic in the magnet ramp program to flatten the rf voltage curve and reduce the peak voltage needed during the cycle was also tried in the ESME simulations. Reductions in peak voltage by ten to twenty percent were achieved. Simulating the use of inductive inserts in ESME has begun, and

initial results suggest that if broad-band passive inductors are used, the inductor can over-compensate the longitudinal space-charge force and cause added bunching (below transition) to produce sub-nanosecond bunches.

Results of the BNL-FNAL proton bunching experiment (E932) carried out at the AGS early in 1997 were reviewed by J. Norem [5]. The method investigated there was to accelerate the beam (3×10^{12} protons per bunch) to about 7 GeV kinetic energy and hold it briefly below transition. The transition energy was then rapidly lowered to near the beam energy with the so-called γ_t jump system. This expanded the rf bucket height so the mismatched beam could rotate a quarter of a synchrotron revolution. The nominal 6 nsec (rms) bunches were shortened in this way to about 2.8 nsec (rms).

INSTABILITY ISSUES

K.Y. Ng presented a talk on "Instabilities and Space-Charge Effects in Proton Driver". He examined longitudinal and transverse microwave and coupled-bunch instabilities, distortion of the rf potential well by space-charge effects, as well as the possibility of compensating the latter effect by inductive inserts in the rings. Ng drew several conclusions, as follows. Space charge is the main factor affecting the stability of the beams. The rings appear to be safe from longitudinal and transverse microwave instabilities. Of course standard stabilizing methods such as active dampers are necessary to counteract some of the instabilities. Flexible momentum compaction lattices would be useful not only to raise the transition energy above the extraction energy but also to allow fast changes in the slip factor to facilitate bunch narrowing manipulations at extraction time. Compensation of longitudinal space-charge effects by means of ferrite-loaded inductive inserts would be useful, especially for the first ring.

ENERGY MEASUREMENT WITH POLARIZED MUONS

R. Rossmanith presented a talk on "Energy Measurement with Polarized Muons". Absolute calibration of the energy of the muon beams in the collider would enable precise measurement of the masses of states such as the Higgs particle formed in the muon-muon collisions. The proposed method is like a muon g-2 experiment run backwards. That is, the energy of the beams can be determined in principle from the well-known value of g-2 by observing the time dependence of the electron spectrum from the decays of a precessing polarized muon beam. Rossmanith concluded that "In principle, high accuracy energy calibration is easily possible", with the caveat that more detailed work is needed.

BOOSTER SLOW EXTRACTION

C. Moore gave a Status Report on work by himself, D. Herrup, J. Lackey, R. Webber, and D. Wolff on the "Feasibility of Slow Extraction from the Booster." This work was motivated by a letter from W. Molzon to D. Finley, FNAL Beams Division, asking whether the Fermilab 8 GeV Booster could be modified to provide beam suitable for the MECO (muon-electron conversion) experiment. It was found that the desired rebunching of the beam into two bunches would take at least 16 msec. Modifications to the Booster guide field power supply that would allow a flattop on the ramp were worked out. A paper design for a slow resonant extraction system was presented. The system would use an electrostatic septum and a Lambertson magnet to extract vertically on the half-integer resonance. Various issues requiring further work were identified. The authors concluded that the idea is "worth further study, close to edge on various issues."

WORKING GROUP PARTICIPANTS

The authors would like to thank the Accelerator Working Group participants for their interesting presentations and efforts during the three-day meeting. The participants were, in alphabetical order, C. Ankenbrandt, M. Brennan, R. Fernow, Y. Fukoi, J. Griffin, Q. Kerns, I. Kourbanis, R. Johnson, C. Johnstone, H.W. Miller, A. Moretti, D. Neuffer, K.Y. Ng, R. Noble, J. Norem, M. Popovic, Z. Qian, R. Rossmanith, W. Wan and D. Wildman.

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